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An Analogue Model of the Geomagnetic Induction in the South Indian Ocean

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Abstract. The role of currents induced in the Bay of Bengal and the Arabian Sea in the response of the Z- and H-components of geomagnetic variations is investigated. Particular attention is paid to the measurements at Annamalainagar at the East coast of Southern India. First, induction arrows are derived which suggest that currents channeled through the Palk Strait between India and Sri Lanka are essential for the observed coast effect. It is shown to be plausible that these currents flow in conductivity enhancements under the shallow waters of the Palk Strait. An analogue model of the ocean water around India has been used to measure the impact of different primary currents and of the presence or absence of the conducting channel of the Palk Strait on the geomagnetic coast effect. The results support the hypothesis expressed in an accompanying paper that primary currents in the ionosphere give rise to responses in ΔZ and ΔH that are different from those of currents flowing in the magnetosphere. Thus the general location of the source current can be distinguished by the readings at just one station like Annamalainagar.

Key words: Annamalainagar – Palk Strait – Geomagnetic coast effect – Induction arrows – Analogue model

Introduction

Near coastlines it is typically observed that geomagnetic variation fields possess an abnormally large vertical component. This is ascribed to the strong conductivity gradients between the sea-water (and the material underneath) and the continental crust. The magnetic field created by time-varying external currents cannot penetrate the regions of higher conductivity (ocean and suboceanic crust) readily. Depending on the thickness of the high conductivity region and the dimensions of the external current, the time required for the magnetic field to diffuse through the better conductor will range from several minutes to several hours. Hence, near coastlines one observes a dependence of the ratio of vertical and horizontal perturbations, $\Delta Z/\Delta H$, on the period. Short-term variations related to geomagnetic bays (substorms) at high latitudes or storm sudden commencements show an entirely different behavior of $\Delta Z/\Delta H$ than the daily variation of the Sq-current system. The whole effect is referred to as the *geomagnetic coast effect* (Parkinson, 1962). A recent review was given by Parkinson and Jones (1979).

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A special situation exists at the geomagnetic observatory at Annamalainagar in Southern India. The Z-component of short-term variations shows completely different responses at night and during the day. This was noticed by Papamastorakis and Haerendel (1974) and formed the subject of the thesis by the first author (Papamastorakis, 1975) of the present work. The explanation of the different responses was given in terms of the latitudinal profile of the primary currents and the resulting differences in the morphology of the currents induced in the ocean. A method was derived to distinguish between ionospheric and magnetospheric sources of the variations based on the ratio of ΔZ and ΔH at Annamalainagar. This has been described in an accompanying paper (Papamastorakis and Haerendel, 1983; referred to as Paper I).

An *analogue model* of the highly conducting Indian ocean was constructed in order to check the hypothesis concerning the role of the morphology of the primary currents. For the primary currents two different conductors were chosen. A narrow one following the magnetic dip equator was intended to resemble the ionospheric current system with its concentration towards the equator, the equatorial electrojet. A significantly broader band conductor was chosen to resemble current sources in the magnetosphere with little latitudinal variation. The results obtained with this model, in particular ΔZ and ΔH measured along the coastlines, form the main subject of this paper.

Before turning to the analogue model we will inspect some actual measurements with regard to the orientation of the conductor carrying the induced currents near Annamalainagar. We apply the method of deriving induction arrows after Wiese (1962), Parkinson (1962) and Untiedt (1964) The subject of particular interest is the role of the shallow Palk Strait between Southern India and Sri Lanka. The induced fields at Annamalainagar would look quite different depending on whether a substantial amount of the induced current is channeled through the Palk Strait or not. This subject has received much attention recently (Nityananda et al., 1977; Rajaram et al., 1979; Takeda and Maeda, 1979; Thakur et al., 1981).

Induction Arrows

Far from the coast, from conductivity anomalies, or strong concentrations of the primary current, the magnetic variation field is horizontal. In approaching the coast an increasing Z-component is noted. This means that the variation field lies in a plane with increasing slope, the "preferred plane". The vector normal to this plane, or better, its horizontal component points away from the better conductor. There are different ways to demonstrate this fact in graphical terms (Wiese, 1962; Parkinson, 1962; Untiedt, 1964). In the following, we shall apply two of these methods for magnetic variations observed at Annamalainagar.

Figure 1 shows two arbitrarily selected nighttime perturbations of about 1-h duration. Following Untiedt (1964) we plot the hodograph of the horizontal perturbation vector (ΔH, ΔD) for these two events separately and connect points of equal value of ΔZ by straight lines. The induction arrow $\vec{Cu}$ is normal to these lines and points towards higher ΔZ. Its length is proportional to the distance between two straight lines for constant ΔZ. Both events give rather similar results. The induction arrow points to 57° and 63°, respectively, west from north. The better conductor should be located in the opposite direction, i.e. approximately 30° south of east. This is shown in Fig. 2. A straight line perpendicular to the two arrows runs parallel to the channel between Southern India and Sri Lanka, the Palk Strait, thus implying that the currents induced in the ocean water are channeled through the Palk Strait in spite of the shallowness of the water (< 30 m).

It should be noted that the determination of induction arrows after Untiedt (1964) leads to great uncertainties concerning the true orientation of the better conductor if the plane of polarization of the selected magnetic perturbation is nearly constant. There is a strong tendency for such behavior in the short-term variations at Annamalainagar, irrespective of time of day.

Before further discussing this subject, we apply another method. Figure 3 contains the ratios $\Delta H/\Delta Z$ plotted against $\Delta D/\Delta Z$ for 43 SSC events in 1968–1970 observed at Annamalainagar. The periods are typically 5–10 min, and the maximum of the amplitudes has been chosen. No selection according to time of day has been applied. Wiese's (1962) method for finding the induction arrow consists of fitting the data by a straight line and determining the vector normal to it. The result differs significantly from the former determination of the induction arrow (Fig. 2). The reason is to be sought in the fact that daytime events have also been included in Fig. 3, with relatively small values of ΔZ. The nighttime values alone cluster between 1.5 and 2.0 for $\Delta H/\Delta Z$ and do not allow a good definition of a straight line. On the other hand, their distribution does not exhibit any clear cut relation to the two induction arrows of Fig. 2.

It was demonstrated in Paper I that pure ionospheric perturbations cause practically zero ΔZ at Annamalainagar. This is the consequence of a superposition of contributions of equal magnitude but opposite sign from the primary ionospheric current and the induced earth current at this location. The latter flows predominantly in the ocean water of the Bay of Bengal, but the sub-ocean floor may contribute significantly, in particular in the shallow water near the coast. The shape of the Bay of Bengal leads to the formation of a large current eddy whose size depends on the distribution of the primary current. We will discuss this subject in detail later in this paper, but refer here to Fig. 9 which shows the induced current vortex for a primary current concentrated at the equator. If the primary current is flowing in the magnetosphere, it should be much more homogeneous in latitude and consequently cause a smaller primary ΔZ. Secondly, the current vortex in the Bay of Bengal would have a different size. It should be shifted northward. Therefore, it is qualitatively clear why such primary perturbation currents cause a finite ΔZ at the location of Annamalainagar and why its sign (positively correlated with ΔH) is that expected from induced currents flowing southward towards the Palk Strait.

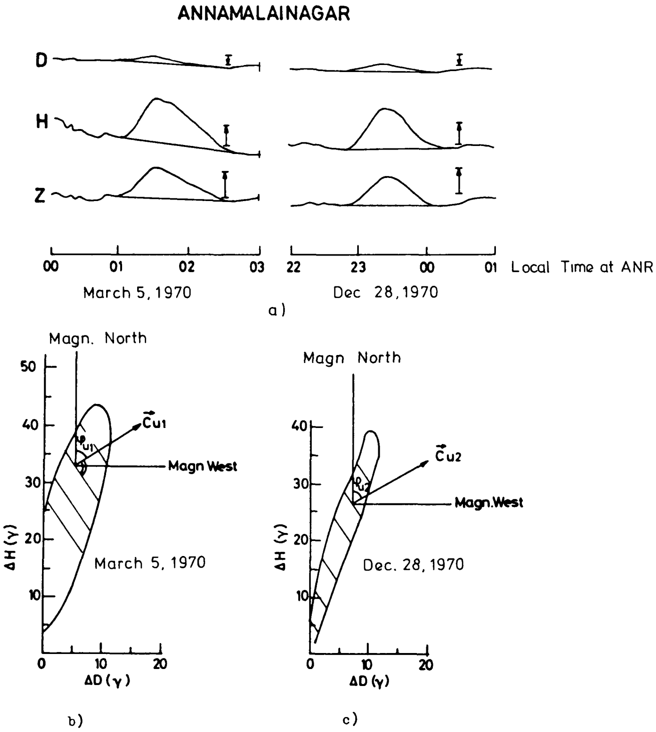

Fig. 1. **a** Two arbitrary nighttime perturbations at ANR. **b** Construction of the induction arrows $\vec{Cu}$ after Untiedt (1964)

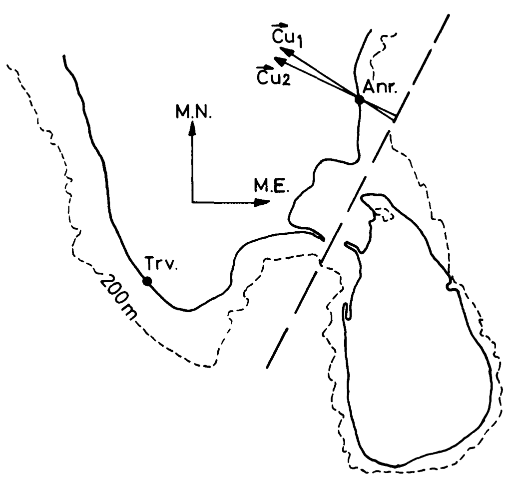

Fig. 2. Induction arrows from Fig. 1 shown in a map. The dashed line indicates the direction of preferred flow of the induction currents. Channeling through the Palk Strait is suggested

We return now to Fig. 3 which was derived from SSC events. As shown in Paper I they are composed of contributions from primary perturbation currents flowing both in ionosphere and magnetosphere. Hence, $\Delta Z \neq 0$ for all events, but ΔZ becomes relatively small during the middle of the day. The determination of the induction arrow, C, according to Wiese suffers from the same deficiency as that according to Untiedt, but more seriously. It lies in the fact that the polarization plane of the primary perturbation

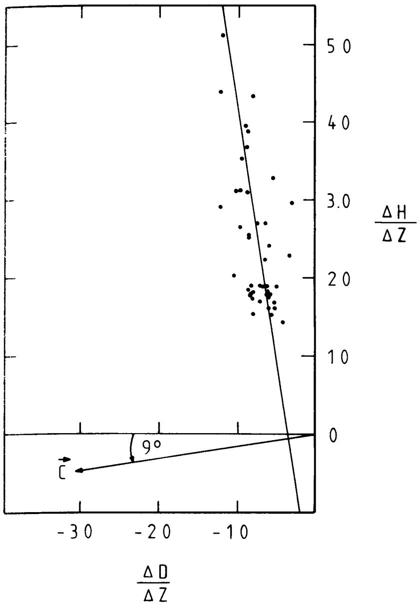

Fig. 3. Construction of an induction arrow, $\vec{C}$ from a large number of SSC events following Wiese (1962).

vector varies very little in the course of the day, and deviates not much from the direction of the coast line. Hence, the straight line fitting the data of Fig. 3 shows essentially the direction of polarization of the primary field. Therefore, we should have higher confidence in the induction arrows derived in Fig. 1, which imply a channeling of induced current through the Palk Strait.

The suggestion that the Palk Strait carries a significant amount of the induced current has attracted much attention. It is interesting that Nityananda et al. (1977) derived significantly different induction vectors for SSC than those shown in Fig. 2, namely between 32.5° and 42.5° west of north. They corrected the readings of ΔH and ΔD at Annamalainagar by subtracting those of Kodaikanal as a normal station. Furthermore, they used only nighttime data. However, the induction vector was not determined by following the method of Wiese (1962), but by taking the mean direction of the so corrected horizontal variations directly. Hence the discrepancy between this work and the present paper is not surprising.

Takeda and Maeda (1979) modeled numerically the induction effect in the ocean water around Southern India and concluded that currents channeled through the Palk Strait play the dominant role for the magnetic variations from SSCs and Bays. Their model includes a finite conductivity for the land. Comparison of the results of this model with observations indicated a spreading of the induced currents into the land mass.

Thakur et al. (1981) investigated the effect with an array of magnetometers spread over Southern India. They concluded that current channeling does indeed exist in the Palk Strait, but that it is difficult to envisage the current as being concentrated in the shallow water of the Strait. It should flow predominantly in the deeper crust or even in the upper mantle.

These results are quite consistent with the induction arrows presented here and with the analogue model results of the present work.

General Considerations

The geomagnetic coast effect is a typical example of the diffusion of magnetic field through a conductor of finite width and complex shape. The diffusion equation is:

$$\frac{\partial B}{\partial t} = D_m \nabla^2 B \tag{1}$$

with D_m being the magnetic diffusivity defined as

$$D_m = (\mu\, \mu_o\, \sigma)^{-1} \tag{2}$$

μ is the magnetic permeability and σ the electrical conductivity. We will set $\mu = 1$.

A time-scale, τ_o, for diffusion through a conductor of thickness, d, is readily obtained from Equation 2:

$$\tau_o = \frac{d^2}{D_m} = \mu_o\, \sigma\, d^2 = \left(\frac{d}{\lambda_s}\right)^2 \frac{2}{\omega}. \tag{3}$$

$\lambda_s = \left(\frac{\mu_o}{2}\sigma\, \omega\right)^{-1/2}$ is the skin depth and ω the frequency.

The diffusion time τ_o is, however, not relevant for our problem in which the linear dimensions L of the primary current exceed by far the thickness d of the conductor (ocean) through which the magnetic diffusion is considered. From the theory of Price (Price, 1967), we can derive a characteristic time-scale, τ_1, for the case $d \ll \lambda_s$ in the thin sheet approximation:

$$\tau_1 = \frac{2d\, L}{\pi\, \lambda_s^2 \omega}. \tag{4}$$

L should be interpreted either as the width or twice the height of the primary current above the conductor (ocean), whatever is the greater number. A measure of the relative diffusion time is $\alpha = \omega \tau_1$. A convenient numerical expression is obtained if we take for the conductivity of ocean water the standard value (e.g. Parkinson and Jones, 1979), $\sigma = 4\, \Omega^{-1} \mathrm{m}^{-1}$, and measure d in units of 10^3 m, L in units of 10^5 m, and the period P in units of 1 h:

$$\alpha = \omega \tau_1 = 0.28\, \frac{d_3 L_5}{P_h}. \tag{5}$$

For $\alpha \gg 1$, the diffusion time τ_1 is long compared with the characteristic period of the magnetic variation considered.

In analyzing the induction fields in Southern India it is revealing to consider the value of the parameter α for typical periods and different ocean depths. The ocean reaches a depth of more than 2,000 m typically within 100–150 km from the coast of Southern India, except near Sri Lanka. Since the distance of a station like Annamalainagar or Trivandrum from the 2,000 m line is less than the width of the primary current, we should get relevant answers concerning the existence of secondary magnetic perturbations at these stations when evaluating Equation 5 with $d \cong 2{,}000$ m ($d_3 = 2$). We consider the equatorial electrojet as the primary current and adopt a value of 650 km ($L_5 = 6.5$) for its equivalent width (cf. Untiedt 1967). We choose three different periods, $P = 16$ h, 1 h, and 0.1 h in characterizing the Sq-, bay- and SSC-type magnetic variations, respectively. In Table 1 we compare the values of α for $d_3 = 2$ with those for an ocean depth of 20 m ($d_3 = 0.02$) which is characteristic for the Palk Strait.

We see that α substantially exceeds unity for periods of 1 h or less and ocean depths exceeding 2,000 m. For

Table 1. α-Parameter (Eq. 5) for Various Periods and Ocean Depths

d_3	P_h	α
2.0	16	0.23
	1.0	3.7
	0.1	37
0.02	16	$2.3 \cdot 10^{-3}$
	1.0	0.04
	0.1	0.37

such perturbations the ocean has still a high magnetic shielding capability. Hence the secondary magnetic variation fields at nearby stations should be appreciable. This is not so for the daily S_q-variations. Therefore, it is no surprise to see that for S_q the response of ΔZ at Annamalainagar is quite different from that of short-term ionospheric perturbations, for which ΔZ happens to vanish as discussed in Paper I. Acutally for S_q-variations, $\Delta Z<0$ and largely reflects the primary field. On the other hand, as far as the ratio of $\Delta Z/\Delta H$ is concerned, there should be little dependence on the period, as along as $\alpha \gg 1$. From this point of view, SSC's and 1-h variations should behave rather similarly. This is consistent with our findings in Paper I.

For ocean depths of 20 m (Palk Strait), $\alpha \ll 1$ even for periods of a few minutes. The magnetic field diffuses through such a thin layer with a time-scale of 2 min. When applied to a channel like the Palk Strait, this time-scale is even shorter because of the channel's limited horizontal extent. The evaluation of the magnetic perturbations for bay-type events would not show any sign of induction in the Palk Strait, if the ocean water were the sole conductor. Even SSC's should cause only a weak coast effect. However, current channeling can modify such a conclusion appreciably, as shown, for instance, by Nienaber et al. (1979) in a study of current channeling in the Vancouver Island region by means of an analogue model. Unfortunately, quantitative comparison with this work is difficult, because two essential parameters are different from ours. The primary field is more homogeneous and the depth of the channel is a factor of 10 higher than in our case. Another way of assessing the importance of current channeling is to compare the overall resistance of the Palk Strait (water only) with that of a path of equal width around Sri Lanka. It is at least by a factor of 20 higher for the case where the skin depth exceeds the depth of the ocean. It is hard to conceive that such a channel would alter the current pattern in the ocean appreciably. Therefore, we are led to the conclusion that the sub-ocean floor plays an important role in channeling the current through the Palk Strait (Papamastorakis, 1975). The same conclusion was reached by Takeda and Maeda (1979) and Thakur et al. (1981). Obviously, the electrical conductivity of this part of the crust must be enhanced. The geophysical significance of this conclusion is not the subject of this paper (cf. Nityananda and Jayakumar, 1981).

Analogue Model

The motivation behind the work summarized in this and the following sections was a *qualitative* study of the geomagnetic coast effect in Southern India (Papamastorakis, 1975). In particular, it was intended to determine the location of the nulls in the vertical component of the total variation field and their displacements when switching from a primary current concentrated within $\pm 3°$ of the dip equator to a much wider one. Furthermore, the ratios of $\Delta Z/\Delta H$ along the coastline are subjects of this study, since they can be readily compared with the values actually observed. Finally, the gross shape of the current vortices induced in the Bay of Bengal and the Arabian Sea could be conveniently determined with the help of the analogue model.

From the diffusion equation and in particular, the dimensionless diffusion parameter, α (Eq. 5). it is obvious how an analogue model has to be scaled. If the scaling of the linear dimensions of the model (index m) and the natural (index n) situations are chosen and the material, i.e. the electrical conductivity, σ_m, of the analogue model has been selected, we have the following relation between the periods of the natural and the model variations of the magnetic field:

$$P_m = \frac{\sigma_m d_m L_m}{\sigma_n d_n L_n} \cdot P_n \tag{6}$$

for $\mu_m = \mu_n$.

A model ocean has been cut from a copper plate of 0.8 mm thickness. This was meant to represent a uniform ocean depth of 4,000 m. Hence, the linear scaling factor for the thickness as well as for the horizontal dimensions of the ocean was $5 \cdot 10^6$. The profile of the (plane) ocean was tailored after the actual coastline, rather than following a contour of constant depth. A cylindrical map projection was chosen. The Palk Strait was included in the first model, as if it had the same depth. This was done in view of the above conclusion that the conductor is to be found in the subocean floor in this area. For comparison, we intestigated a second model in which the Palk Strait was cut out of the ocean profile. In a further modification of this model, the Palk Strait was represented by a thin copper foil bridging the cutout and corresponding to a conducting layer of 40 m of ocean water.

The equatorial electrojet was represented by a steel band of 13 cm width ($\hat{=}$650 km) and 3 mm thickness ($\hat{=}$15 km) at a height of 2.2 cm ($\hat{=}$110 km). The total model which is shown in Fig. 4a had a size of 2 m × 1 m.

The magnetospheric current source was simulated by a steel band of 40 cm width ($\hat{=}$19° of latitude) at a height of 15.5 cm. A picture of the model with the broad primary current is shown in Fig. 4b.

The choice of materials for ocean and primary currents was on the one hand dictated by simple practical considerations, like the ability to cut a complex profile. More important was the aspect that there should be a significant ratio between the height-integrated conductivities of ocean and primary current conductors, in order to keep mutual induction effects from "ocean" to primary conductor low. In the real world the ratio of the integrated conductivities of ocean and source region is of the order of 50. The corresponding ratio for the model is 13.

The conductivity σ_n of ocean water is $4\ \Omega^{-1}\mathrm{m}^{-1}$; that of copper is $\sigma_m = 6 \cdot 10^7\ \Omega^{-1}\mathrm{m}^{-1}$. The natural and model permeabilities, μ, are essentially unity. Hence we obtain from Equation 6 the following relationship between the natural and model periods:

$$P_m = 6 \cdot 10^{-7}\ P_n. \tag{7}$$

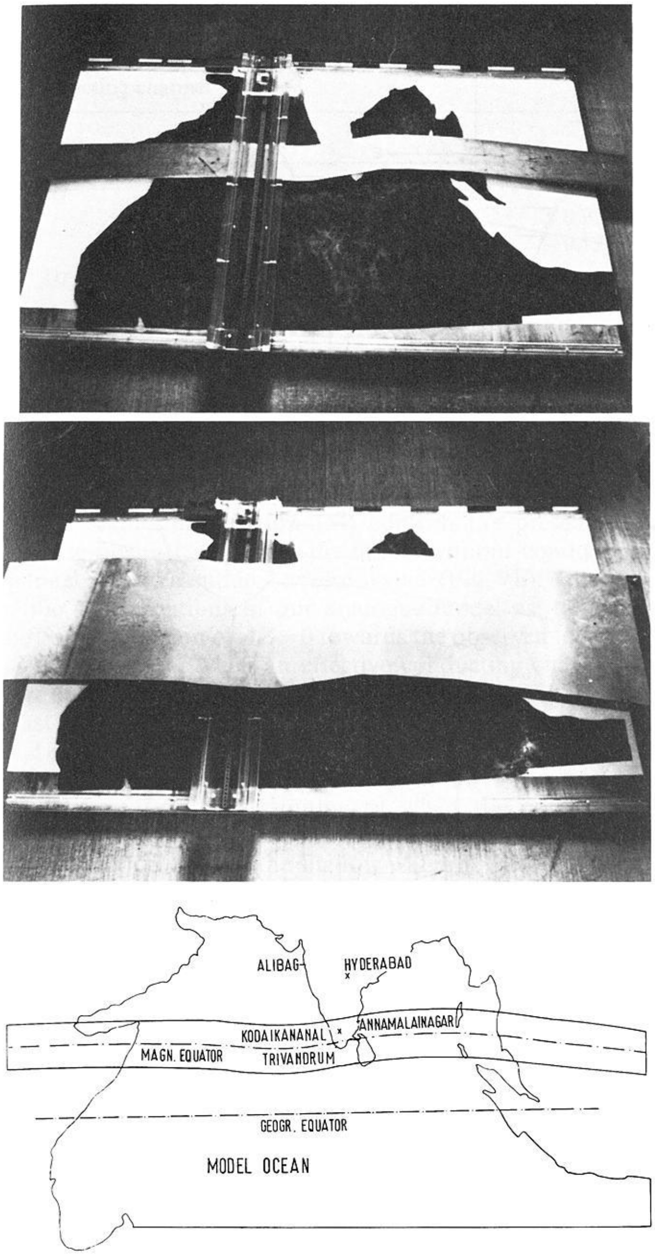

Fig. 4a–c. Photographs and map of the analogue model, **a** with narrow current band representing the equatorial electrojet, **b** with broad band representing a current in the magnetosphere, **c** map corresponding to **a**. The model ocean has a constant thickness of 0.8 mm (≙4,000 m depth). The overall dimensions are 1 m × 2 m

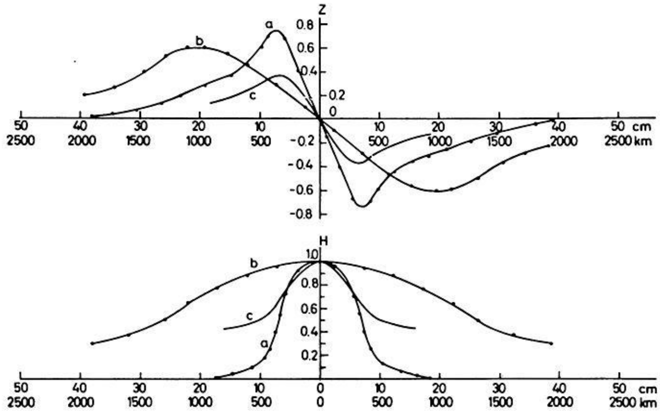

Fig. 5a–c. Z and H components of three different primary currents as function of distance from the equator, **a** for narrow model current, **b** for broad model current, **c** for electrojet according to Untiedt (1967)

A natural period of 1 h is scaled down to $2.16 \cdot 10^{-3}$ s (≙465 Hz). This is the frequency with which the primary current was generated. Its amplitude was 7.5 A. Special care was taken with the feeds to the primary generator. They were physically separated from the model as much as possible. Furthermore, helical winding of the wires to the diagnostic probe was employed. Several tests consisting of displacements of instruments, wires, etc. showed that mutual inductions in the various conductors surrounding the model could be kept so low that the perturbation on the measured fields did not exceed 2%.

The magnetic field probe consisted of a small coil of 1.5 mm inner diameter and 1.5 mm length with 100 windings. Each component of the magnetic field was measured with a special probe mounted in X, Y and Z directions. The voltage induced in the probes ranged from 1–100 V. The magnitude as well as the phase relative to the primary current was measured. The total error in the measurements ranged from 2–5%, partially caused by inaccurate reading, partially due to errors in the phase of the signal ($\pm 5°$). Near the "coastline", where the magnetic field has strong gradients, errors of a few percent were introduced by the finite size of the probe. The positioning of the probe had an accuracy of 0.5 mm (≙2.5 km).

Results Obtained with the Analogue Model

Before we discuss the measurements obtained with the full model, we should compare the applied primary magnetic fields with those of the equatorial electrojet. This is shown in Fig. 5, giving the latitudinal profiles of H and Z at ocean level normalized to $H=1$ at 0° magnetic latitude. Curves a and b represent the fields of the narrow and broad primary currents of the analogue model, respectively, whereas curves c were taken from Untiedt's (1967) theoretical model of the equatorial electrojet. The measurements were carried out in the absence of the copper plate representing the ocean. The profiles of our narrow primary current (a) and Untiedt's electrojet model (c) resemble each other quite closely and differ much from the broad-band model (b). However, the main simplification which we applied in the analogue model, namely to completely neglect the currents flowing outside about $\pm 3°$ magnetic latitude, shows up as a decay of the H-component at higher latitudes which does not exist in Untiedt's more realistic model of the equatorial current concentration. Equally, the vertical component of our model reaches unrealistically high amplitudes. These differences should be borne in mind when interpreting the coast effect of the analogue model.

In the light of the findings described in Paper I, we were mostly interested in the differences of the coast effect introduced by different degrees of homogeneity of the latitudinal distribution of the primary currents. However, we wanted to do this with a sufficiently realistic model of the conductivity distribution at the earth's surface. Therefore, we concentrated initially on the role of the channeling of

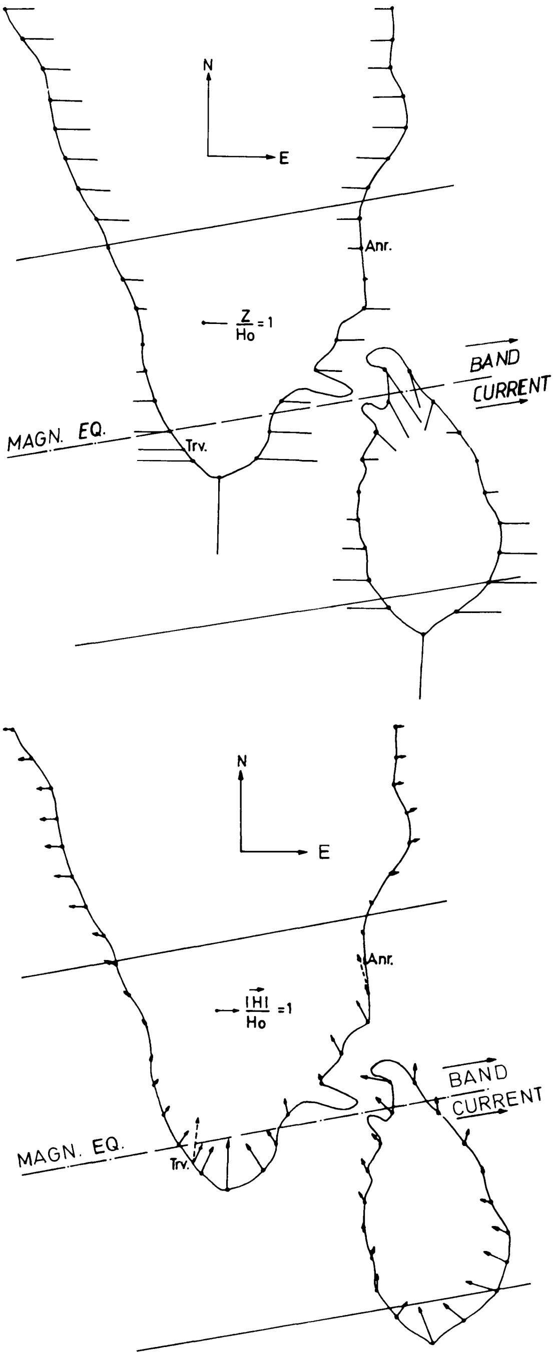

Fig. 6a and b. Normalized Z and H components measured with the analogue model along the coast of Southern India for variations of $2.16 \cdot 10^{-3}$s period. The solid lines parallel to the magnetic equator show the boundaries of the applied primary current. A conducting channel exists between India and Sri Lanka. **a** Bars extending into the ocean indicate $\Delta Z < 0$, bars extending inland indicate $\Delta Z > 0$. **b** The arrows represent the induced horizontal component only. The dashed arrows at TRV and ANR show the total perturbation field

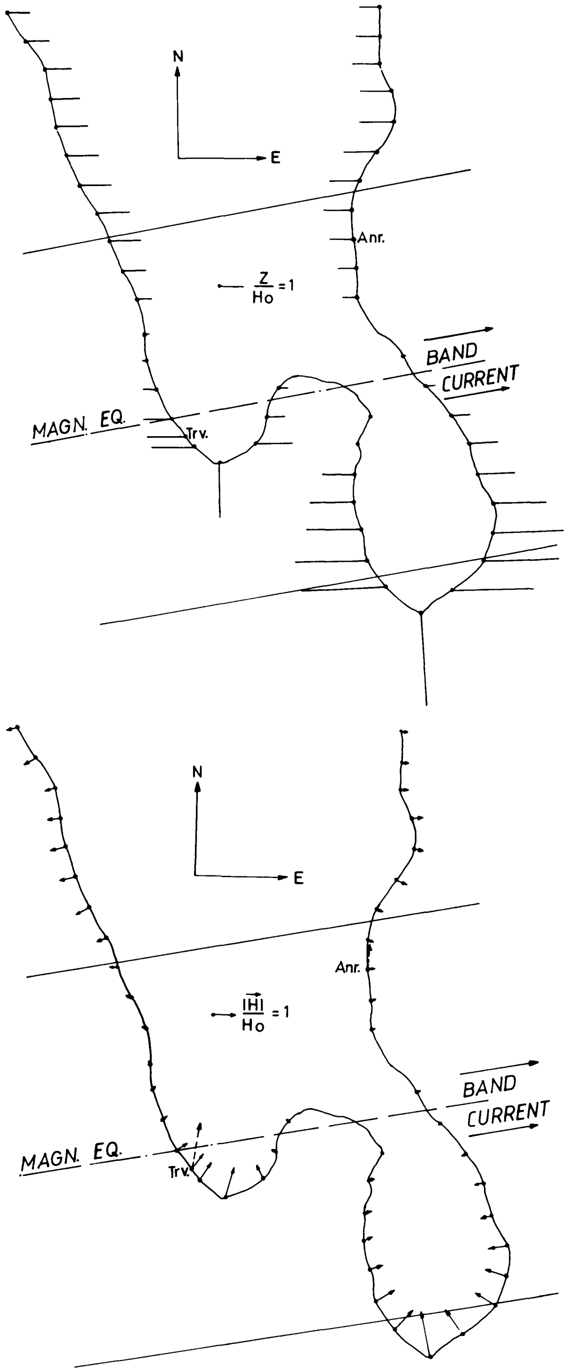

Fig. 7a and b. Same as Fig. 6 without a conducting channel at the Palk Strait. **a** Z-component, **b** induced part of H-component

currents through the Palk Strait. Figures 6a and 7a show, for comparison, the vertical components of the total field with and without the Palk Strait for the narrow primary current representing the daytime situation. The field is normalized to the primary H-component (H_0) at ocean level underneath the electrojet axis in the absence of the model ocean plate. Positive values of ΔZ are indicated by bars pointing from coast to ocean; negative ΔZ by bars pointing inland. Measurements were made every 1 cm ($\hat{=}$50 km) along the coast. Figures 6b and 7b show the induced part of the H-component only, using the same normalization. Only at ANR and TRV do we show the total H-component.

The most significant differences naturally appear in the Palk Strait and over Sri Lanka. Attention should be given to the position of $\Delta Z = 0$ on the east coast. The zero appears 3 cm south of ANR in the model without Palk Strait corresponding to 150 km and only 0.8 cm ($\hat{=}$40 km) south of

Table 2. Some ratios of magnetic variations with $\Delta Z=0$ at Annamalainagar, *a* from magnetograms, *b* from analogue model, primary field only, *c* from analogue model, total field, with Palk Strait as conducting channel

Ratio	Station	*a*	*b*	*c*
$\Delta Z/\Delta H$	ANR	0	−0.63[a]	0[a]
	TRV	+0.95	+0.1	+0.92
	KOD	+0.1	−0.43	−0.19
$\Delta D/\Delta H$	ANR	−0.24	−0.18[a]	−0.26[a]
	TRV	+0.05	−0.11	+0.2
$\Delta H_{TRV}/\Delta H_{ANR}$	–	+1.12	+1.08	+1.30

[a] reading at 0.8 cm south of ANR point

ANR in the presence of a conducting channel. Recent measurements of Thakur et al. (1981) in the Palk Strait at Adiramapattinam (their station D4) confirm the presence of a strong positive ΔZ where the model without conducting channel gives essentially a zero value (Fig. 7b). In spite of the simplifications of our analogue model we take the shift of the position of $\Delta Z=0$ towards the observed location on the east coast when an effective conducting channel is introduced as strong evidence for its existence. On the west coast the Palk Strait channel has little effect. The values of ΔZ and ΔH at Trivandrum and further north are essentially unchanged. Here, the position of $\Delta Z=0$ moved by only 0.4 cm (≙20 km) southward when the conducting channel was removed.

The model in which the shallow water of the Palk Strait was represented by a thin foil bridging the gap in the model ocean plate did not yield induced fields near Annamalainagar that were noticeably different from those obtained by the model without Palk Strait. Channeling in the shallow water only is obviously insignificant.

A better quantitative judgement of the validity of the analogue model can be obtained by comparing the ratios $\Delta Z/\Delta H$, $\Delta D/\Delta H$ for various stations and the ratio $\Delta H_{TRV}/\Delta H_{ANR}$ as found from pure ionospheric perturbations (i.e. $\Delta Z=0$ at ANR) with the readings of the analogue model. This is done in Table 2. Instead of taking the measurements at a point corresponding to the geographic location of Annamalainagar, we took then at the equivalent location of the analogue model, namely where $\Delta Z=0$ in the model (i.e. 0.8 cm south). This is indicated by an asterisk.

The comparison of columns *b* and *c* shows clearly the importance of the induction fields for ΔZ and ΔD. Furthermore, it is seen that the observed values at ANR and TRV are reasonably well reproduced by the model. The positive value of $\Delta Z/\Delta H$ at Kodaikanal is not quite obtained by the model, but the induction fields drift ΔZ in the right direction. This may be taken as an indication of a conductivity gradient in the crust underneath the Indian subcontinent (compare Murty and Swamy, 1978). If the model ocean had been tailored to follow the contour of 2,000 m depth, $\Delta Z/\Delta H$ would have been much closer to the primary field value (column *b*). The ratio of $\Delta H_{TRV}/\Delta H_{ANR}$ is mainly determined by the primary fields. The induction fields make the agreement slightly worse.

The next step is the comparison of the variations caused by narrow and broad primary currents. Figure 8 shows the Z-component for the latter in the presence of a conducting channel. This is to be compared with Fig. 6. We see a displacement of the $\Delta Z=0$ positions by 2.3 cm (≙115 km) northward on the east coast and even by 4 cm≙200 km on the west coast. This shift is the main point to note. It confirms the hypothesis expressed by Papamastorakis and Haerendel (1974) (see Paper I) that the appearance of a positive $\Delta Z/\Delta H$ at ANR is a consequence of the wider latitudinal extent of primary currents flowing in the magnetosphere. The sign of the model Z-component is as observed, only its magnitude is somewhat lower than the actual value (≈60%). This is likely to be due to the limitations of the truncated model ocean, the flat earth model, and other unexplored subtleties such as sub-surface conductivity structure. On the other hand, a small but noticeable increase of $\Delta Z/\Delta H$ between narrow and broad primary currents as actually observed for TRV (from 0.95 to 1.21, see Paper I) is also found with this model.

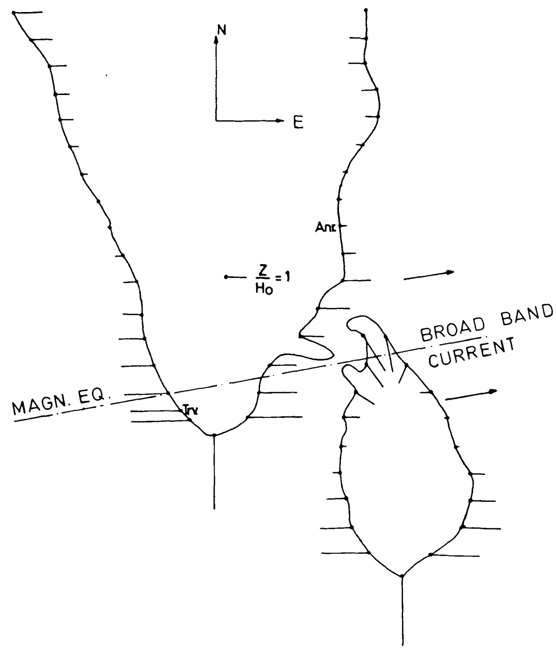

Fig. 8. Z-component for a broad primary current in a model with conducting channel at the Palk Strait

In order to obtain an idea of the distribution of the currents induced in the Arabian Sea and the Bay of Bengal we measured the electric field on the bottom side of the copper plate representing the ocean. This was done by voltage measurements between two fine steel spikes separated by 1 cm which were pressed into the copper plate. The induced current density is proportional to the electric field which was found to be essentially in phase with the primary current. The measurable shift was ranged between 10° and 20° in the sense that the electric field was leading the primary current. The flow lines of the electric current (perpendicular to the equipotentials) are shown in Fig. 9 for a narrow primary current. Although the model extended well below the lower rim of this figure (compare Fig. 4) the results become increasingly unreliable for southern latitudes because of the artificial cutoff of the conductor. The main features to observe are the two current vortices in the Arabian Sea and the Bay of Bengal and the channeling of current through the Palk Strait. As indicated by the shift of the locations of $\Delta Z=0$, the southern extent of the vortices shrink by 100–200 km when a broad primary current is applied.

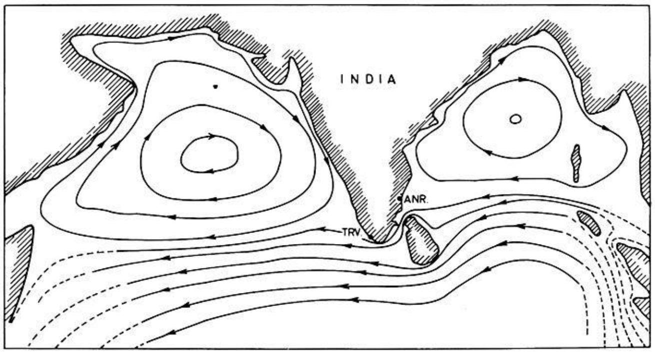

Fig. 9. Current flow lines as deduced from electric potential measurements at the bottom of the model ocean with conducting channel and for the narrow primary source current. The southern contours have been omitted because of edge effects

As a final step we studied the possible influence of a zone of increased conductivity at great depth underneath the continents as discussed by many researchers (e.g. Parkinson and Jones, 1979; Chan et al., 1981). To this end we placed a 3 mm thick copper plate at 6 cm ($\triangleq$300 km) underneath the surface level. As expected we observed a reduction of the coast effect on ΔZ ($\approx$25% at TRV) but no qualitative change of the described results.

Summary

We investigated essentially two questions concerning the geomagnetic coast effect in Southern India, the influence of a concentration of the primary current to a region of a few degrees width around the equator as compared with a broad profile in latitude, and the influence of a conducting channel through the Palk Strait on the readings of ΔZ and ΔH at the east coast, in particular. Induction arrows derived from magnetic perturbations seen at Annamalainagar as well as the measurements with the analogue model favor the existence of a conducting channel. It is argued that the currents rather than being concentrated in the shallow seawater flow predominantly in a layer of highly conducting material under the ocean floor. Such conductivity enhancements in the subocean crust have been postulated by many researchers. Careful studies with magnetometers on either side of the Palk Strait extending into India and Sri Lanka, in particular studies of the dependence of $\Delta Z/\Delta H$ on period would be needed to derive more quantitative conclusions on the spatial extent of the conductivity enhancements. This is outside the scope of this paper.

Our main aim was to support conclusions described in Paper I on the separability of primary current sources in ionosphere and magnetosphere. The analogue model gives this support. It shows that the points of $\Delta Z=0$ at the crust are at substantially different locations for narrow or wide primary currents. This is mainly a consequence of the difference in the magnitude of the primary ΔZ, on which the secondary ΔZ of the induced currents is superposed. The latter currents are forming vortices in the Bay of Bengal and the Arabian Sea whose sizes shrink with increasing width of the primary current. Zero secondary ΔZ is found where the southern edge of the vortex meets the coastline. Our model with narrow primary current gives a location of the zero at the east coast almost precisely where it is actually observed, namely close to Annamalainagar. For broad primary currents, $\Delta Z/\Delta H$ is found to be positive at this station, in accordance with the observations.

This paper complements Paper I which deals with the observations of geomagnetic variations. Taken together we are now provided with a tool allowing us to separate ionospheric and magnetospheric origins of any short-period magnetic variation in the Asian sector. In a further publication we will apply this tool to bay-type and SSC-type magnetic perturbations and to the question of penetration of electric fields to low latitudes.

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